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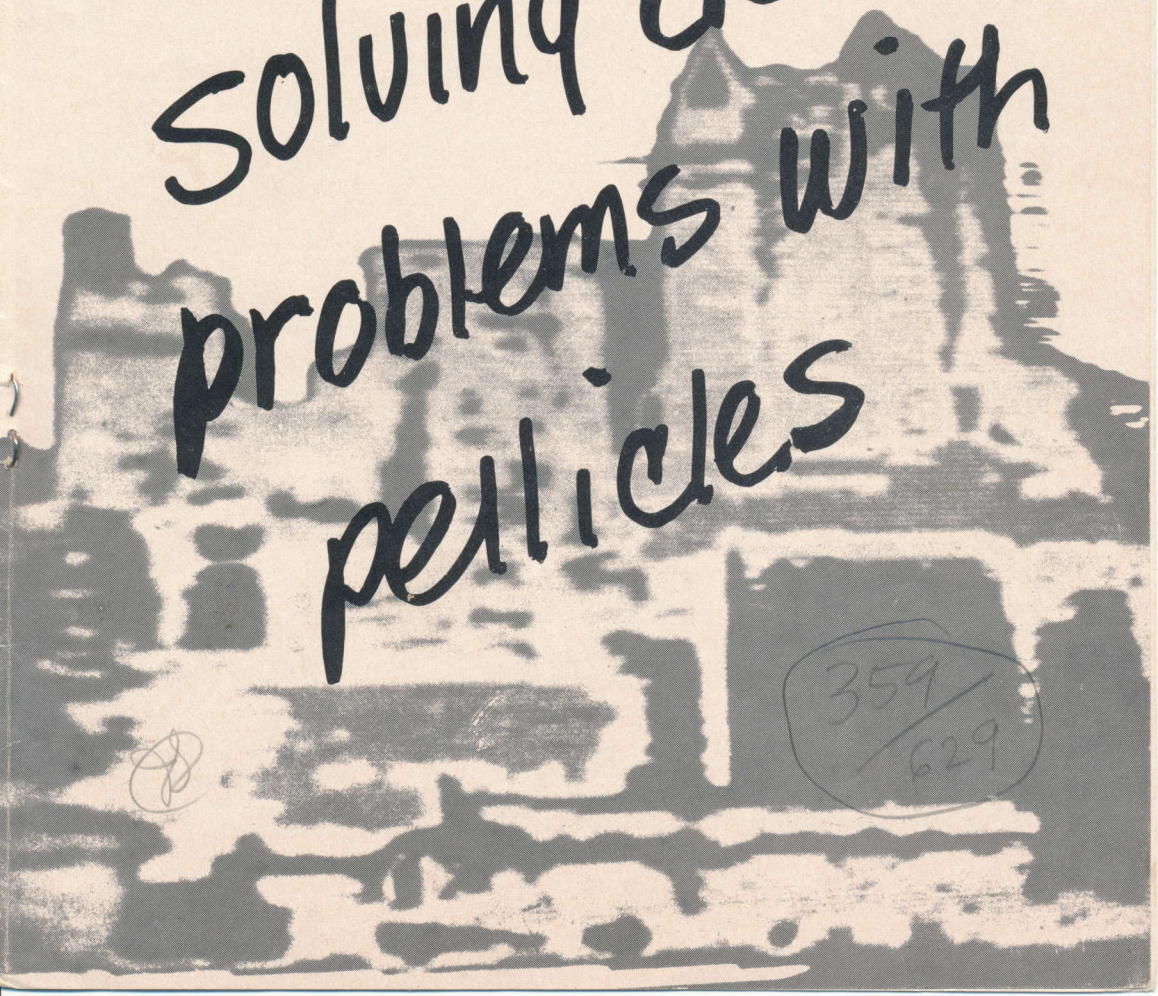
solving design problems with pellicles



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SOLVING DESIGN PROBLEMS WITH PELLICLES

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The pellicle, not to be confused with a fish-eating bird, is a thin membrane that can split beams, polarize light and reflect images with little or no optical "side effects". This "old but still new" component is being used to solve many of today's sophisticated electro-optical design problems.

Although used as windows, mirrors, and polarizers, it is as a beam splitter, particularly, that the pellicle has proven the most valuable to the systems designer. In this form, the pellicle has done jobs, easily and neatly, that were difficult or impossible using more conventional components.

The pellicle has been used in a number of instruments to split a convergent or divergent beam of light without causing an optical shift in focus or chromatic aberation. For example, Grumman Aircraft Corporation uses pellicles in precision autocollimating theodolites where displacement of the line of sight would disturb calibration of the device. For a microdensitometer offering simultaneous viewing and scanning, Photo - Metric Data Systems uses pellicles to avoid refractive errors. Princeton University uses a nine-inch diameter pellicle (coated as a 40-40 beam splitter) in a high-speed automatic scanner for bubble chamber films. This pellicle had to be flat to two waves over the central seven-inch circle and with a quarter wave per inch around the circumference.

One of the major reasons for interest in pellicles is basically this: in the normal use of a beam splitter it is generally desirable that the beams remain unperturbed. Producing a semi-reflection plane for this purpose is relatively easy, but supporting this plane without perturbing the beams can be a problem. The usual solution is glass—either a plane-parallel sheet with the semireflector on one side or two right prisms cemented to form a cube with the partically reflecting surface running at 45° between two opposite edges. The rub here is double-barrelled. Even assuming that the glass is optically perfect, flat and free from striae, spurious reflections will occur at the air-glass interfaces. Refraction within the glass will cause an optical path length change and for the sheet beam splitter a lateral image shift also. If necessary, these effects can be countered in the mechanical design of the device. The worst problem, however, is that the index of refraction is a function of the wavelength of the light, and the refractive effects are not spectrally uniform. Thus in convergent light, color aberration will be introduced, and only a major redesign of the optical system will cure it. This is where the pellicle comes in. Although the pellicle is theoretically susceptible to the same problems, because of its gossimer-like thickness, the perturbation to the transmitted beam becomes less than the wavelength of light, and cannot be detected. Thus, for the optiker, the pellicle fulfills the dream of a flat, zero-thickness beam splitter.

An Old And Venerable Device

Early experimenters were fascinated with the production and use of pellicles. For example, one reference to this technology is found in an 1899 publication.[1] The experimentalist used pellicles as closures for acoustic resonators (his paper was communicated by Lord Raleigh) and realized that very light-weight mirrors could be made by using a flat-faced mounting ring. His greatest problem, not solved to his complete satisfaction, was in depositing a silver coating using Brashear's process.

Other early references to the applications for pellicles are found in the patent and trade literature for one-shot color camers. Wall, in his monumental "History of Three-Colour Photography"[2] includes many formulas for the collodion and dye filters. A British patent[3] describes the use of unsupported pellicle filters for one-shot three-color cameras.

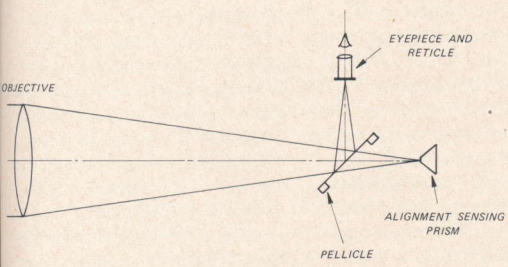

Fig. 1. Optical alignment theodolite uses pellicle to present identical scenes to eyepiece and sensing prism.

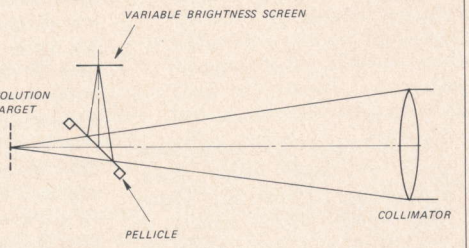

Fig. 2. Pellicle-equipped projection collimator with variable contrast target.

Fabrication

The pellicle itself is just a very thin plastic film. Historically, the film has been formed by a type of "float-casting": the material, dissolved in a suitable solvent, is poured onto smooth water, and the solvent allowed to dry. As the process became more sophisticated it also became proprietary, and today's pellicle fabrication is a complex and closely guarded art.

Cellulose nitrate, man's first plastic, has some unusual properties that make it a unique optical membrane material. Despite the fact that some applications require the membrane to be water-proof, most do not. The fact that the material is hygroscopic is used to good advantage in its application to the holder. By stretching the water-soaked membrane over a flat lapped frame, an extremely taut flat film is produced when the membrane dries. If the elastic limit of the material is not exceeded the pellicle retains its flatness over a wide range of temperatures and humidity.

The flatness of a pellicle is determined by the mount to which it is bonded. For large pellicles, the design of a flat mount that will remain flat in the instrument becomes a formidable engineering problem. A ring surface is readily lapped to optical flatness by ordinary optical shop procedures. To maintain this precision in service, however, it is necessary to use highly stiff materials to avoid self-distortion in the ring, and kinematic mounting techniques to prevent deformation from mounting stresses or friction. Thermal effects also must be minimized since thermal gradients and the resulting differential expansions can also introduce distortion to the pellicle surface.

Co-incident with the publication of this paper, the announcement by National Photocolor of a novel approach to the manufacture of high quality pellicle flats, suitable for interferometer use, is expected. The pellicle will utilize a flat lapped, high alumina ceramic ring with a modulus of elasticity in excess of 40 x 10^6 psi. Mounting distortion is eliminated with the coupling of a mating aluminum holder allowing the assembly to be positioned at any angle without introducing a measurable distorting moment.

Applications

Uses for pellicles abound. They can be used almost anywhere a beam splitter is required and some places where the more conventional glass counterparts cannot.

One such use is to present an image to two detectors simultaneously. For example, in an automatic optical alignment theodolite, **Fig. 1,** the initial target acquisition is obtained visually by using a pellicle to present the same field to an eyepiece as to the position sensing prism. Once the operator has approximately centered the target, the automatic sensor servos it to a null. A relatively large aperture objective is employed, and the pellicle is positioned in the convergent beam, reflecting a portion of the image into the eyepiece. Because of its extreme thinness, the pellicle transmits the remainder of the beam to the sensor essentially undeviated and undistorted. The requirements on quality for the reflected beam are moderate because the field is visual, and need only be positioned to within the linear range of the sensor. Similarly, a pellicle can be used between lens and film for a nulling type automatic exposure control for a photographic system. The pellicle deflects (samples) a small portion of the main image beam. This sample falls on a photodetector which servo-controls the diaphragm to main-

—glass can introduce color aberration in focused light . . .

tain the image illuminance constant. The main beam passes undisturbed to the film plane. Here again, pellicle quality is not critical as it has a negligible effect on the main beam, and image quality to the photodetector is not a consideration. Use of a cube or glass plate beam splitter, however, introduces a detrimental color aberration into the main beam as well as causing a marked shift in the focal plane.

Another use of pellicles is for the simultaneous or selective projection of two optical fields. A typical application is for collimators where the contrast in the resolution target at the focal plane must be altered, **Fig. 2.** The target is transmitted undistorted through the pellicle while a uniformly illuminated field of variable brightness is optically superimposed on it by reflection. Because the reflected field is uniformly illuminated, very loose tolerances can be placed on distortion by the pellicle. Once again, the thinness of the pellicle permits its use in a divergent beam.

Pellicles have been used successfully in so many varied applications that a complete listing would be impractical. In the vision research field, images from two different sources can be presented to the eye, with the viewer seeing the combined image as coming from source. The images, while superimposed spatially, can be alternated or mixed temporally for certain investigations. Pellicles have also been used as high quality windows, maintaining a hermetic seal without distorting optical measurements made through them. They have also been useful as self-destructing or externally destructible windows.

In general, where two fields are combined by a beam splitter, one of them is more critical than the other. This dictates which field is to be transmitted and which can be reflected, for the transmitted field is practically unaffected by the pellicle, while the reflected field is degraded by any lack of flatness in the pellicle surface. A system can therefore be designed using a pellicle in a convergent beam to satisfy the requirements of superimposed fields without suffering the optical aberrations, multiple images, and stray light commonly associated with flat plate beam splitters or beam splitting cubes.

Vibration—Beat It or Use It

With large pellicles (current technology permits consideration of sizes up to the order of 16 in.) mechanical and acoustical vibrations become critical. Such pellicles may have resonant frequencies well below 100 Hz and must be isolated from such frequencies to keep the reflected field from being blurred by its motion. Of course, the transmitted field is impervious to any motion of the pellicle. Because of their drum-head like tension and extremely light weight, pellicles are sensitive to very weak acoustical coupling through the atmosphere. They must, therefore, be isolated not only from mechanical vibrations through the use of anti-vibration mounts, but also from acoustical effects by being enclosed in a housing that cannot transmit acoustical waves.

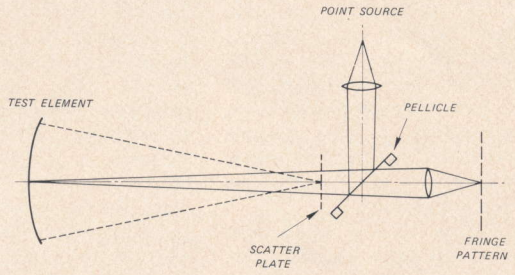

Fig. 3. Scatter plate interferometer.

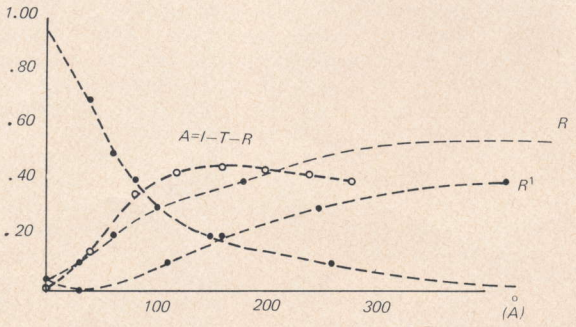

Fig. 4. Characteristic variation of metal film parameters with thickness.

One application for pellicles uses this acoustical sensitivity to good advantage. In the scatter-plate interferometer, **Fig. 3**, a beam splitter is used to illuminate the scatter plate and the optical element being tested, and to view the resulting fringe pattern. When a laser is used as a light source, the resulting fringe pattern overlays a relatively course speckle resulting from interference between the closely spaced scattering centers in the scatter plate. This speckle is annoying in that it reduces the clarity of the desired fringes. By exciting the pellicle with an appropriate musical tone, it can be made to vibrate at resonance, displacing the reflected laser beam cyclically over a small distance. The fringe pattern is essentially unaffected by this motion but the speckles may be completely washed out.

Pellicle Interferometry

The most critical application of the pellicle as a beam splitter is in interferometry where each of the two beams (reflected as well as transmitted) must remain undistorted. The technology of fabrication has progressed to the point where interferometric-quality pellicles can be made. Therefore in discussing the optical properties of pellicles we can consider those of importance to interferometry, although for many applications requirements can be relaxed. These properties are intimately associated with the thin film coatings applied to the pellicles.

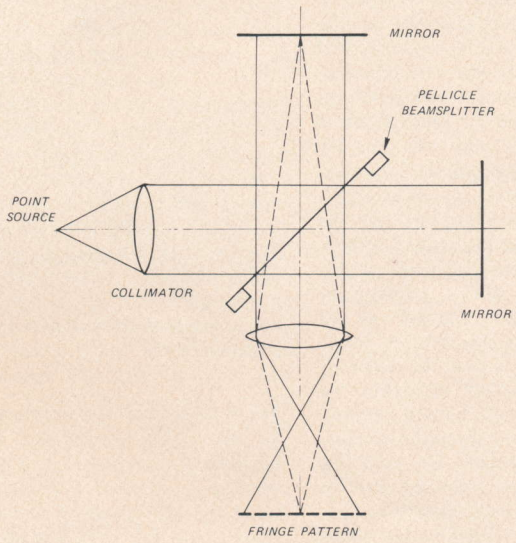

Fig. 5. Twyman-Green two-beam interferometer.

A metallic film can be deposited (usually in vacuum) to produce any desired amount of either reflection or transmission. Because of the inherent absorption, only one of these parameters is independent. Since reflectance varies with the angle of incidence of light, this angle must be given if close adherence to reflectance specifications is necessary. For all non-zero angles of incidence (zero angle of incidence means normal incidence, i.e. perpendicular to the surface) some separation of directions of polarization is experienced by the light on reflection and transmission. If the introduction of such a separation of polarization cannot be tolerated in the light reflected or transmitted by the pellicle, its parameters have to be tailored to this requirement. Polarization effects introduced by metallic films are much less than those resulting from dielectrics. As the thickness of a thin metallic film increases, its absorbance varies from zero to some maximum value and then diminishes, becoming equal to (1—R) (where R = reflectance of the bulk material) when the film becomes opaque.

Reflection and Absorption

Interestingly enough, although the transmission is independent of the direction of incidence through the pellicle and metal film, the reflectance and absorbance are not. Fresnel's equations for the reflectance from a plane surface show that it depends on the ratio of the refractive indices of the two media separated by the surface. The more this ratio departs from unity, the higher the reflectance. Since the index of the pellicle is higher than that of air and lower than that of the metal, the air-to-metal reflectance will be greater than the air-to-pellicle and pellicle-to-metal reflectances, even if they sum constructively.

The multiple internal reflec-

—a very thin metallic film yields zero reflectance . . .

tions in the metallic film do not compensate for this difference, in fact they tend to enhance it in some instances. Since transmittance, reflectance, and absorbance must all sum to unity, as reflectance varies so does absorbance.

Fig. 4 gives the characteristic reflectances of a metal film from its two sides as a function of its thickness. Included is the transmission curve, permitting calculation of the absorbance. Of particular interest is the zero reflectance produced by a very thin metallic film from its second surface. This is almost wavelength independent, annihilating the reflectance for the greater part of the visible spectrum. Because of this, it is useful for eliminating the reflectance from the back surface of the pellicle (and thereby eliminating interference effects between its two surfaces) provided that the higher reflectance from the air-to-metal surface does not hinder its use.

Because the reflectance is different for light incident from opposite directions, metallic films produce some undesirable effects when used as beam splitters in interferometry. In the conventional two beam interferometer employing a beam splitter, **Fig. 5**, the two beams each suffer a reflection and transmission at the splitter, their resultant energy being given by the product of the reflectance and transmittance. However, one beam undergoes an air-to-metal reflection while the other encounters a pellicle-to-metal interface. Therefore the energy in the second beam will be less than in the first since the transmittances are the same. This results in reduced contrast fringe patterns since highest contrast fringes result only from interfering beams of equal intensitiy.

For this reason dielectric films are often used for interferometer beam splitters. Since they have negligible absorbance they produce equal reflectances from either direction. Although Fresnel's equations again predict that the air-to-dielectric reflectance is higher than the pellicle-to-dielectric reflectance the multiple reflections in the film assure that the resulting reflectances are the same.

Polarization Rears Its Head

Although dielectric films are superior to metallic films in yielding equal reflectances regardless of direction of light passage, they introduce much greater changes in the polarization of the reflected and transmitted beams. For light incident on a plane surface at any angle other than zero, the amount of light reflected (as well as the phase shift on reflection) will depend on its state of polarization. Its state of polarization can be designated by considering it to consist of only two linearly polarized components vibrating at right angles to each other. The two components may be aligned along any pair of orthogonal axes provided their amplitudes and phase angles are appropriately assigned to be equivalent to the incident beam. It is usual to use the plane of incidence as the reference for these two polarization components. This is the plane containing the incident ray and the normal to the reflecting surface at the point of incidence. One component is selected as polarized in the plane of incidence, that is its vibrations are only in this plane, the other is polarized perpendicular to this plane. The former is designated as p-polarization; the latter as s-polarization. Each of these components experiences a different reflectance and phase shift, the values of which are given by Fresnel's equations. The multiple reflections in the dielectric films may be tallied independently for the two polarizations, there being no energy exchange between them. After reflection the two components are added vectorially to establish the new state of polarization for each beam. Only parallel components of polarization are able to interfere to produce fringes.

Many interferometers have coplanar normals for all their mirrors. In this case, a simple way to avoid an imbalance in the two beams resulting from polarization effects is to linearly polarize the incident beam either, in or perpendicular to the common plane of incidence for all mirrors. Both interfering beams then maintain the same state of polarization and are thereby capable of producing the highest contrast fringe patterns.

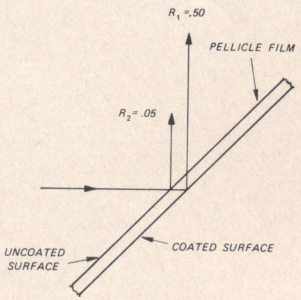

Fig. 6. Source of interference pattern in beam splitting pellicle.

The Pellicle Itself Can Interfere

In some interferometers the beam splitter is placed in a converging or diverging beam instead of the usual collimated beam. This can give rise to an interference pattern caused by the pellicle itself that overlays the main fringe pattern. The contrast in the pattern produced by the pellicle depends on the values of the reflectances at its two surfaces. For light incident on the uncoated side of the pellicle, **Fig. 6**, the reflectance might be 0.50 at the coated surface and

0.05 at the other surface giving a 10:1 ratio in their intensities. The contrast in the fringe pattern is determined by adding and subtracting the amplitudes of these two beams to determine the maxima and minima in the fringe pattern. Since the amplitudes are the square roots of the reflectances, they are 1.00 and 0.31 respectively. The maxima are thus $(1.31)^2 = 1.72$ while the minima are $(0.69)^2 = 0.47$ resulting in a relatively contrasty pattern which would probably be quite undesirable. If an anti-reflection coating is applied to the rear surface so that its reflectance is reduced to 0.01, or a 50:1 ratio in their intensities, a similar calculation shows that the maxima and minima are 1.30 and 0.74 respectively. While this is a greatly reduced contrast, it is by no means negligible, and indicates the desirability of coating the back surface of the pellicle with an even lower reflectance film.

Not only is this fringe pattern undesirable aesthetically, its presence introduces a distortion in the main pattern. Wherever a fringe of the main pattern crosses one from the pellicle pattern, it becomes discontinuous, curving away from the pellicle fringe in opposite directions on either side of the break. In most instances these artifacts can be ignored, recognizing that they don't originate in the optical element being tested, and with an efficient anti-reflection coating they can be made to disappear.

The reason the pellicle pattern can exist at all is that the optical path producing the fringes varies with the angle of incidence, and a non-collimated beam will include differing incidence angles, **Fig. 7.** For a plane parallel pellicle of thickness "d" a new fringe will appear whenever $2nd/\lambda \cos \theta'$ changes by an integer. (n is the refractive index of the pellicle, λ the wavelength of the light, and θ' the angle the light ray makes with the normal to the pellicle surface within the pellicle.) A commonly employed pellicle has $2nd/\lambda \approx 30$ so that a new fringe will appear as at the intervals where $\cos \theta'$ changes by 0.033. The fringes will appear at infinity as arcs of concentric circles, the center being found in the direction of the perpendicular to the plate of the pellicle viewed from the image point of the non-collimated light. If collimated light is employed, a fringe pattern can be observed located in the plane of the pellicle whenever the thickness, d, of

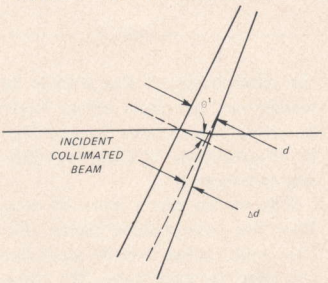

Fig. 8. Geometry for fringe formation in wedged pellicle.

the pellicle changes enough to make $2n\triangle d/\lambda \cos\theta' = 1$, where $\triangle d$ is the thickness change. This pattern contours the change in optical thickness, $\triangle(nd)$, of the pellicle, **Fig. 8.**

If an interferometer is designed so that the energy is incident on the beam splitter at Brewster's angle, **Fig. 9,** and

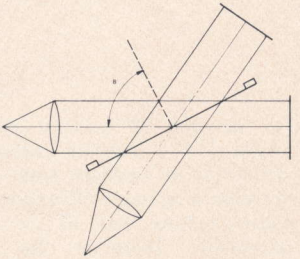

Fig. 9. Interferometer employing Brewster angle incidence, θ_B, to eliminate interference in the beam splitter.

only the p-component is used, all interference effects will be eliminated for an uncoated back surface. The first surface coating must be designed for the desired reflectance of the p-component, and the back surface reflectance will be zero.

Another useful application of pellicles is as a "pile-of-plates" polarizer. If a number of pellicles are oriented approximately parallel to each other and at the proper angle to an incident, unpolarized beam, the transmitted beam can be made highly polarized, **Fig. 10,** the degree of polarization depending directly on

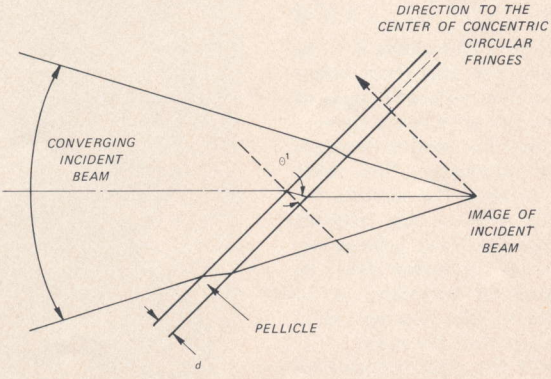

Fig. 7. Geometry for fringe formation in plane-parallel pellicle with non-collimated incident illumination.

one polarization is transmitted—the other partly reflected . . .

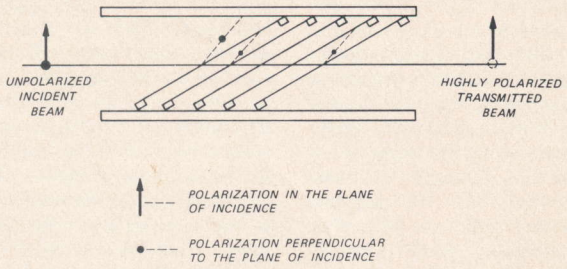
UNPOLARIZED INCIDENT BEAM
HIGHLY POLARIZED TRANSMITTED BEAM
POLARIZATION IN THE PLANE OF INCIDENCE
POLARIZATION PERPENDICULAR TO THE PLANE OF INCIDENCE

Fig. 10. Pile-of-plates polarizer.

the number of pellicles employed. For, a dielectric surface inclined to an incident beam at the polarizing angle (Brewster's angle) reflects none of the p-component. Therefore the p-component increases with the number of surfaces encountered.

A calculation of this attenuation of the s-component is readily achieved by using the law that the ratio of R/T for the whole stack is equal to the sum of r/t for each surface. (R, r = reflectance; T, t = transmittance.) If we have N pellicles, with 2N surfaces each having the same value of r and t, R/T = 2Nr/t.

Now Fresnel's equations show that at the polarizing angle

$$r = \left(\frac{1 - n^2}{1 + n^2}\right)^2 = 0.15 \text{ for } n = 1.5$$

(n = refractive index of pellicle.)

Therefore,

$$\frac{r}{t} = \frac{0.15}{0.85}, \text{ and } \frac{R}{T} = 0.353N,$$

but $R = 1 - T$, therefore

$$\frac{R}{T} = \frac{1}{T} - 1, \text{ and } T = \frac{1}{1 + 0.353N}$$

so that with 20 pellicles T = 1/8. This indicates that the s-component has been reduced to 1/8 of its original intensity, while the p = component has been transmitted without attenuation. This calculation includes the multiple reflections between the pellicles, and assumes that interference effects are eliminated either by the thickness variations in the pellicles or the non-monochromaticity of the light beam.

One of the important uses for such a stack of pellicles is for polarizing a high energy laser beam. Over the visible spectrum the absorbance of the pellicle is negligible, so that even high powered pulsed laser beams may be transmitted without producing any damage.

The writer has a word of caution for prospective users. He has seen cases where pellicles are used as substitutes for glass beam splitters only after the user has found that a ghost image, or refraction of the transmitted beam, was troublesome. Too often, in these cases, the pellicle has to be mounted on a frame that is insubstantial, creating distortion in the reflected beam. Pellicles designed into a system at the start offer a greater chance of success.

Pellicles, properly used, can supply the answer to many optical problems. Imaginatively used, they can open up new paths for the researcher and the production man. □

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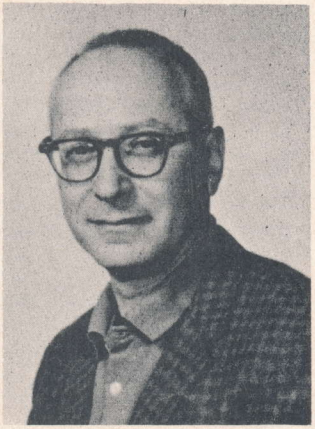

Author Milton J. Schwartz, President of National Photocolor Corporation, has been actively engaged in both electronics and optics for most of his business career. As a photographic technician he became the Director of the Research & Q. C. Laboratory for Dufaycolor, Inc., and headed up the first commercial quantity color print operation in the country for Dufay. He helped develop a new, high speed x-ray intensifying screen during World War II, and subsequently went into the sales end of the electronic flash business representing EG&G. Working closely with Dr. Harold Edgerton, he developed his own Kilojoule flash apparatus which he manufactured and sold to commercial photographers. He acquired the National Photocolor Corp. in 1956 and has worked since then on many improvements in both quality and application of pellicles.